

**EVOLUTION OF SHOCK MELT COMPOSITIONS IN LUNAR REGOLITHS.** A. M. Vance<sup>1</sup>, R. Christoffersen<sup>2</sup>, L. P. Keller<sup>3</sup>, E. L. Berger<sup>4</sup>, S. K. Noble<sup>5</sup> <sup>1</sup>Department of Geology, Beloit College, 700 College St, Beloit, WI 53511(vancea@beloit.edu), <sup>2</sup>Jacobs, NASA Johnson Space Center, Mail Code XI3, Houston, TX 77058, USA (roy.christoffersen-1@nasa.gov), <sup>3</sup>NASA Johnson Space Center, Mail Code XI3, Houston, TX 77058, USA, <sup>4</sup>GCS-Jacobs-NASA Johnson Space Center, Mail Code XI3, Houston, TX 77058, <sup>5</sup>NASA Headquarters, 300 E St SW Mail Code 3D75, Washington DC 20546

**Introduction:** Space weathering processes – driven primarily by solar wind ion and micrometeorite bombardment, are constantly changing the surface regoliths of airless bodies, such as the Moon [1]. It is essential to study lunar soils in order to fully understand the processes of space weathering, and how they alter the optical reflectance spectral properties of the lunar surface relative to bedrock [1, 2].

Lunar agglutinates are aggregates of regolith grains fused together in a glassy matrix of shock melt produced during micrometeorite impacts into the lunar regolith. The formation of the shock melt component in agglutinates involves reduction of Fe in the target material to generate nm-scale spherules of metallic Fe (nanophase Fe<sup>0</sup> or npFe<sup>0</sup>) [3]. The ratio of elemental Fe, in the form of npFe<sup>0</sup>, to FeO in a given bulk soil indicates its maturity, which increases with length of surface exposure as well as being typically higher in the finer-size fraction of soils [2,4].

The melting and mixing process in agglutinate formation remain poorly understood. This includes incomplete knowledge regarding how the homogeneity and overall compositional trends of the agglutinate glass portions (agglutinitic glass) evolve with maturity. The aim of this study is to use sub-micrometer scale X-ray compositional mapping and image analysis to quantify the chemical homogeneity of agglutinitic glass, correlate its homogeneity to its parent soil maturity, and identify the principal chemical components contributing to the shock melt composition variations. An additional focus is to see if agglutinitic glass contains anomalously high Fe sub-micron scale compositional domains similar to those recently reported in glassy patina coatings on lunar rocks [5].

**Samples and Methods:** The lunar soil samples were obtained from the curation facilities at Johnson Space Center. A polished grain mount of Apollo 11 soil, 10084, was used to develop and improve image analysis techniques. Data collection was done on pre-polished grain mounts of Apollo 17 mare soil samples 73241, 78501, 76281, and 78421, with approximately 16-21% Al<sub>2</sub>O<sub>3</sub> and varying maturity (respective I<sub>s</sub>/FeO ratios: 18, 36, 45, 92) [6]. Back scatter electron images of agglutinitic glass were collected using the JEOL JSM-7600F field-emission scanning electron microscope at NASA JSC. Quantitative element maps were

collected by compositional spectrum imaging. The map pixels were quantified into values of wt. % oxides, with pixel values in agglutinitic vesicles removed from the dataset. Numerical methods were devised to plot the oxide compositions of each onto ternary diagrams to create large, highly spatially resolved datasets showing mixing trends and relationships of the glass. Soil samples 73241 and 78501 were also characterized using the JSA-8530 field-emission electron probe microanalyzer in order to test the accuracy of the SEM data.

**Results:** Our image-based compositional analysis technique using the SEM yielded ternary variation diagrams similar to those obtained by microprobe, but with a factor of 10 to 100 higher density of points. Removal of data contained in pixels associated with holes was very effective, but it was generally not possible to remove the composition of entrained minerals from the dataset. The microprobe readings of both 73241 and 78501 showed plagioclase rich glass mixtures, with a Fe content above what was expected. These results are similar to those collected on the same areas using the SEM, which show that the SEM mapping technique can be used to accurately plot agglutinitic glass composition.

Agglutinates in the least mature soil, 73241 (Fig. 1a,b), have dominantly Al<sub>2</sub>O<sub>3</sub> rich glass, with a wide ranging TiO<sub>2</sub> content. The FeO content lies primarily on or above the mixing line of ilmenite and pyroxene (Fig. 1b). The average glass composition of soil 78501 is Al<sub>2</sub>O<sub>3</sub> rich, with a relatively low TiO<sub>2</sub> component (0-40%). The bulk of the FeO data lies well above the ilmenite-pyroxene mixing line, with parts of the distribution extending to 100% FeO ranges. Soil 76281 has an Al<sub>2</sub>O<sub>3</sub> rich average glass composition. The TiO<sub>2</sub> composition ranges from 10-80% from grain to grain. The FeO composition spans both below and above the mixing line of ilmenite and pyroxene.

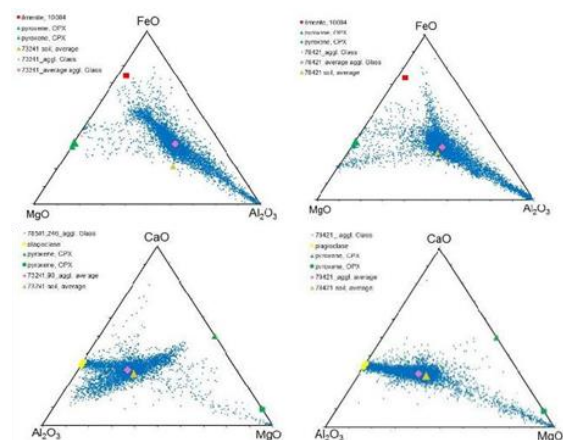
The most mature soil, 78421 (Fig. 1c,d), has a composition that fluctuates primarily between Al<sub>2</sub>O<sub>3</sub> and MgO, with very little TiO<sub>2</sub> content (typically 0-30%). The FeO content plots on or above the ilmenite-pyroxene mixing line (Fig. 1d).

**Discussion:** The average melt composition across the samples is a plagioclase rich mixture with varying degrees of input from ilmenite and pyroxene. The pla-

gioclase enrichment could reflect the greater susceptibility of this mineral to undergo shock melting, or modal variations in the regolith target [7].

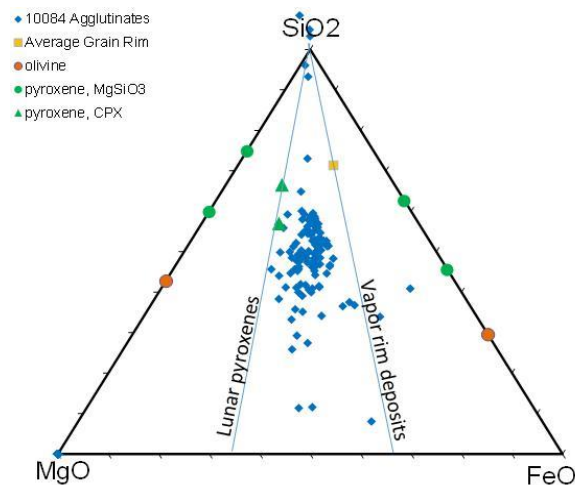
Our results do not show a correlation between soil maturity and agglutinitic glass compositional homogeneity. There was too much variation between individual agglutinate grains in the same soil. However, this could be a result of the small number of glassy areas that were mapped and analyzed. The mapped regions were also chosen by visual inspection, and are not necessarily representative of the more intricate portions of agglutinitic glass in the grains.

The agglutinitic glass FeO content was found to be consistently higher than the ilmenite-pyroxene mixing line in all samples (Fig. 1b,d) requiring a source of Fe other than from these mineral contributing to the glass. By using standard normative subtractive measures, it is possible to calculate and plot the residual FeO, MgO and SiO<sub>2</sub> unassociated with either plagioclase or ilmenite, and contributed by pyroxene and olivine. These data (Fig. 2) show a unique compositional cluster which could be interpreted as having an olivine and pyroxene source, but overall has a much higher Fe/Mg ratio than typical lunar mare pyroxene and olivine compositions. There are several possibilities to explain this excess FeO over MgO. The first is that it is being derived from previously produced agglutinitic glass, which is high in Fe. However, this does not explain where the high amounts of FeO in the original agglutinitic glass came from initially. Another option is that the FeO is coming from Fe deposits in the micrometeorite impactors. One final possibility is that these FeO anomalies are coming from Fe vapor rims, which are deposited around mineral grains during bombardment



**Figures 1a,b.** Compositional ternary diagrams of agglutinitic glass in least mature soil 73241. **Figures 3c,d.** Compositional ternary diagrams of agglutinitic glass in most mature soil 78421.

and loss of volatiles. These rims form primarily around grains in the finest fraction, which would support the fusion of the finest fraction theory [5,8,9]. The average Fe/Mg ratio of vapor rims found in patina is slightly higher than the residual values found in the agglutinitic glass. The low volume of Fe rich vapor rims indicates that there is most likely a combination of sources for the surprisingly large amounts of FeO.



**Figure 2.** Plot of the residual FeO, MgO and SiO<sub>2</sub> in the agglutinitic glass of sample 10084.

**Conclusion:** The chemical homogeneity of agglutinitic glass is not tied to maturity. The composition and homogeneity of the glass is determined by the target material, and individual mixing events are too stochastic to define parameters.

The high FeO content of the glass indicates that ilmenite and pyroxene are not the only contributors to the composition. The residual FeO could be attributed to a combination of melting high Fe pyroxene and olivine grains, and melting Fe vapor rim deposits around the finest fraction of soil grains.

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**References:** [1] Pieters, C. M. et al. (2000) *Meteoritics & Planet Sci.*, 35, 1101-1107. [2] Taylor, L. A. et al. (2001) *JGR*, 106, 27985-27999. [3] Shkuratov, Y. G. et al. (2007) *Solar System Research*, 41, 177-185. [4] Taylor, L. A. et al. (2000) *Meteoritics & Planet Sci.*, 36. [5] Christoffersen, R. et al. (2014) *LPS XXXV*, Abstract. [6] Morris, R. V. (1978) *Proc LPS Conf 9<sup>th</sup>*, Abstract, 2287-2297. [7] Schaal, R. B. and Hörz, F. (1980) *Proc LPS Conf 11<sup>th</sup>*, 1679-1695. [8] Papike, J. J. (1981) *LPS XII*, abstract, 805-807. [9] Walker, R. J., and Papike, J. J. (1981) *Proc LPS*, 12B, 421-432.